Mapping the Milky Way Galaxy with LISA

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Abstract

Gravitational wave detectors in the mHz band (such as LISA) will observe thousands compact binaries in the galaxy which can be used to better understand the structure of the Milky Way. To test the effectiveness of LISA to measure the distribution of the Galaxy, we simulate the Close White Dwarf Binary (CWDB) gravitational wave sky using different models for the Milky Way. To do so, we have developed a Galaxy density distribution modeling code based on the Markov Chain Monte Carlo method. The code uses different distributions to construct realizations of the Galaxy. We then use the Fisher Information Matrix to estimate the variance and covariance of the recovered parameters for each detected CWDB. This is the first step towards characterizing the capabilities of space-based gravitational wave detectors to constrain models for Galactic structure, such as the size and orientation of the bar in the center of the Milky Way.

Introduction

One of the science goals of LISA is to understand and map the structure of the Galaxy and the distribution of close white dwarf binaries (CWDBs). One way of achieving this goal is to obtain sky locations for individually resolvable CWDBs along with distances for chirping CWDBs. The Mock LISA Data Challenges (MLDCs) have shown that we can expect to resolve $\sim 20,000$ binaries. A large number of these systems (those at frequencies > 4 mHz) will be distributed homogeneously throughout the galaxy. In order to estimate the degree to which LISA observations can constrain Galaxy structure models, we anticipate modeling the errors expected from typical data analyses and applying the results to a variety of Galaxy models spanning astrophysically reasonable structure parameters. We model the CWDB parameter estimation errors from different Galaxy models containing a bar and from this recovered catalog of CWDBs determine if LISA is able to detect this Galactic structure.

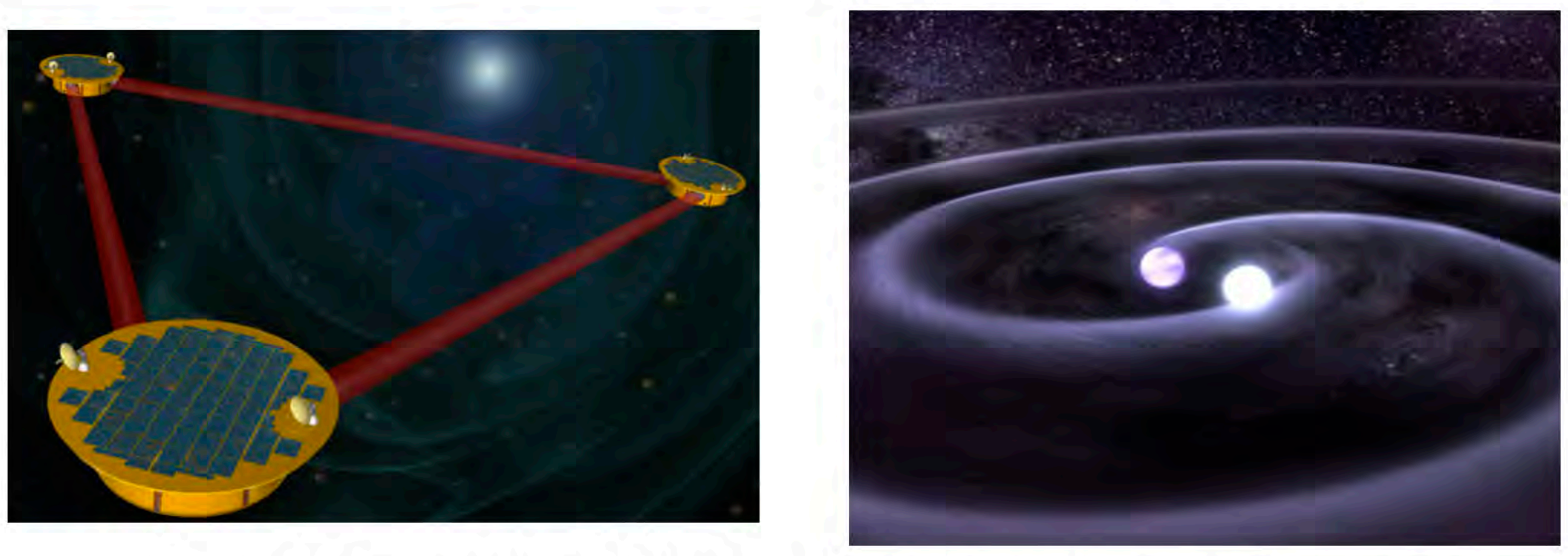

Figure 1: LISA detector (Right) and a White Dwarf binary star propagating gravitational waves(Left)

Process

We begin with a catalog of approximately 27 million CWDBs containing derived from population synthesis simulations of the Galaxy. Using this distribution we can Monte Carlo over each binaries position in the galaxy, and orientation with respect to the LISA detector, to produce different Galaxy models according to the different density profiles shown in Eq 1 – 8. A Markov Chain Monte Carlo algorithm was used to generate new instances of each Galaxy model – in other words, with every run of the code we generate a new Galaxy.

After obtaining different Galaxy models we determine which binaries are detectable using a signal-to-noise (SNR) threshold of 7. From this subset of detectable binaries, the Fisher Information Matrix is used to estimate each binary's parameter uncertainties. A further selection is made on those which are resolved by LISA to within 1 $\deg^2$ on the sky, and with there luminosity distance d_L measured to within 10%. This subset of spatially-resolved binaries will be used in future work to constrain the distribution of the Galaxy.

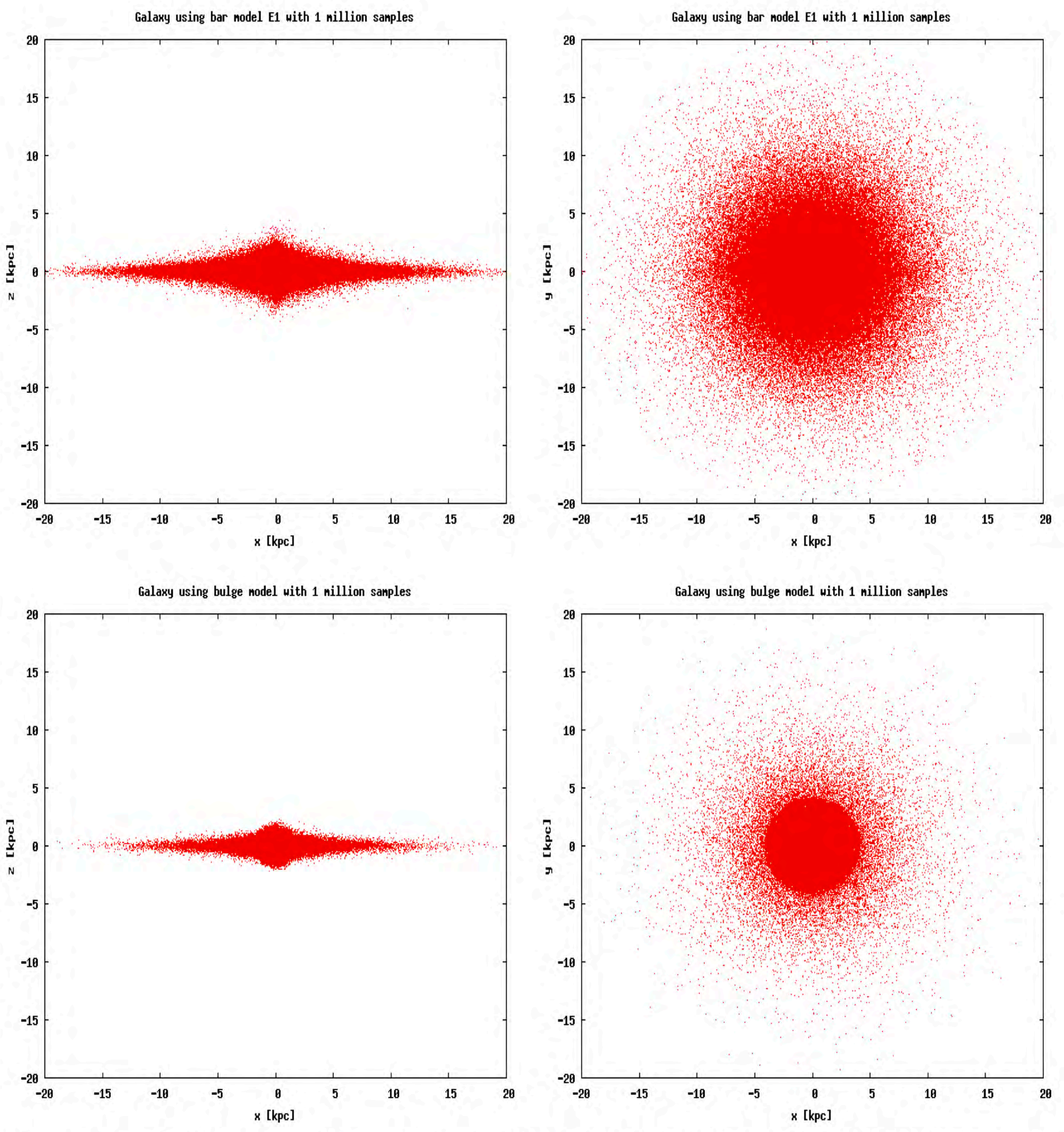

Figure 2: Front view of a Galaxy model using best bar model E1 (top left) and the bulge (bottom left) with their respective top views (top right and bottom right respectively).

References

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The Disk's Galactic Distribution

We start to populate the disk of the Galaxy by selecting R and z from the probability density function (PDF)

$$\rho(R,z) = \rho_{0D}\, e^{-R/R_d}\, e^{-z/z_d} \tag{1}$$

with scaleheight z_d, scalelength R_d and normalization constant ρ_{0D}.

The galactic disk lies in the x-y plane. The distribution of stars is assumed to be cylindrically symmetric, so the azimuthal angle θ is uniformly drawn from $0 < \theta < 2\pi$. We then compute the cartesian galactic coordinates of each binary via $x = R\cos(\theta)$, $y = R\sin(\theta)$, and $R = \sqrt{x^2+y^2}$.

The Milky Ways disc is usually considered to have two major components: a thin disc and a thick disc (e.g. Gilmore & Reid 1983). As described in Juric et al.(2008), the scalelengths R_d for the thin and thick discs are 2.6 kpc and 3.6 kpc, respectively, with a quoted uncertainty of 20 per cent in each case, and the best-fitting values for the scalengths are $z_{d,thin}$ = 300 pc and $z_{d,thick}$ = 900 pc. In this treatment, we only consider a single disk distribution with scale height $z_d = 300pc$.

The Bulge and Bar's Galactic Distribution

We populate the Bar of the Galaxy by using the probability density functions used in the analytic models described by Dwek et al. (1995). The density functions are the following:

$$\rho_{G1} = \rho_0\, e^{-r^2/2}, \tag{2}$$

$$\rho_{G2} = \rho_0\, e^{-r_s^2/2}, \tag{3}$$

$$\rho_{E1} = \rho_0\, e^{-r_e}, \tag{4}$$

$$\rho_{E2} = \rho_0\, e^{-r}, \tag{5}$$

$$\rho_{P1} = \rho_0 \left(\frac{1}{1+r}\right)^4, \tag{6}$$

$$\rho_{P3} = \rho_0 \left(\frac{1}{1+r^2}\right)^2, \tag{7}$$

$$\rho_B = \rho_{0B}\, e^{-R^2/R_b^2}, \tag{8}$$

where

$$r = \left[\left(\frac{x}{x_0}\right)^2 + \left(\frac{y}{y_0}\right)^2 + \left(\frac{z}{z_0}\right)^2\right]^{1/2}, \tag{9}$$

$$r_e = \frac{|x|}{x_0} + \frac{|y|}{y_0} + \frac{|z|}{z_0}, \tag{10}$$

$$r_s = \left\{\left[\left(\frac{x}{x_0}\right)^2 + \left(\frac{y}{y_0}\right)^2\right]^2 + \left(\frac{z}{z_0}\right)^4\right\}^{1/4}, \tag{11}$$

and the normalization for the bulge's distribution function is

$$\rho_{0B} = \frac{1}{(\sqrt{\pi}R_b)^3}. \tag{12}$$

The coordinate system has the origin at the GC, with the xy plane defining the mid-plane of the Galaxy and the z-direction parallel to the direction of the Galactic poles.

Model	β	α	x_0	y_0	z_0
G_1	0.75	27.06	1505.20	568.49	392.19
G_2	-7.68	24.49	1276.56	473.28	359.91
E_1	1.95	23.82	1901.43	626.89	324.93
E_2	0.97	26.43	986.60	356.65	260.88
P_1	2.19	25.30	1810.98	609.40	478.93
P_2	3.67	25.16	3513.34	1160.72	927.54

Table 1: Best-fitting parameter values for all density models (equations 2 to10) with Bar orientations (β and α) in degrees and scale lengths (x_0, y_0 and z_0) in parsecs.

5. Conclusion

From the different Galaxy models used, it was observed that many of the LISA resolvable CWDBs will be coming from the bar and bulge as seen in figure 3. This due to the high concentration of sources located in these Galactic structures. From this results it is intended in future work to constrain the distribution of the Galaxy. Other Galactic structures can be implemented in the models such as the addition of spiral arms and globular cluster for more realistic models (as many papers suggest).

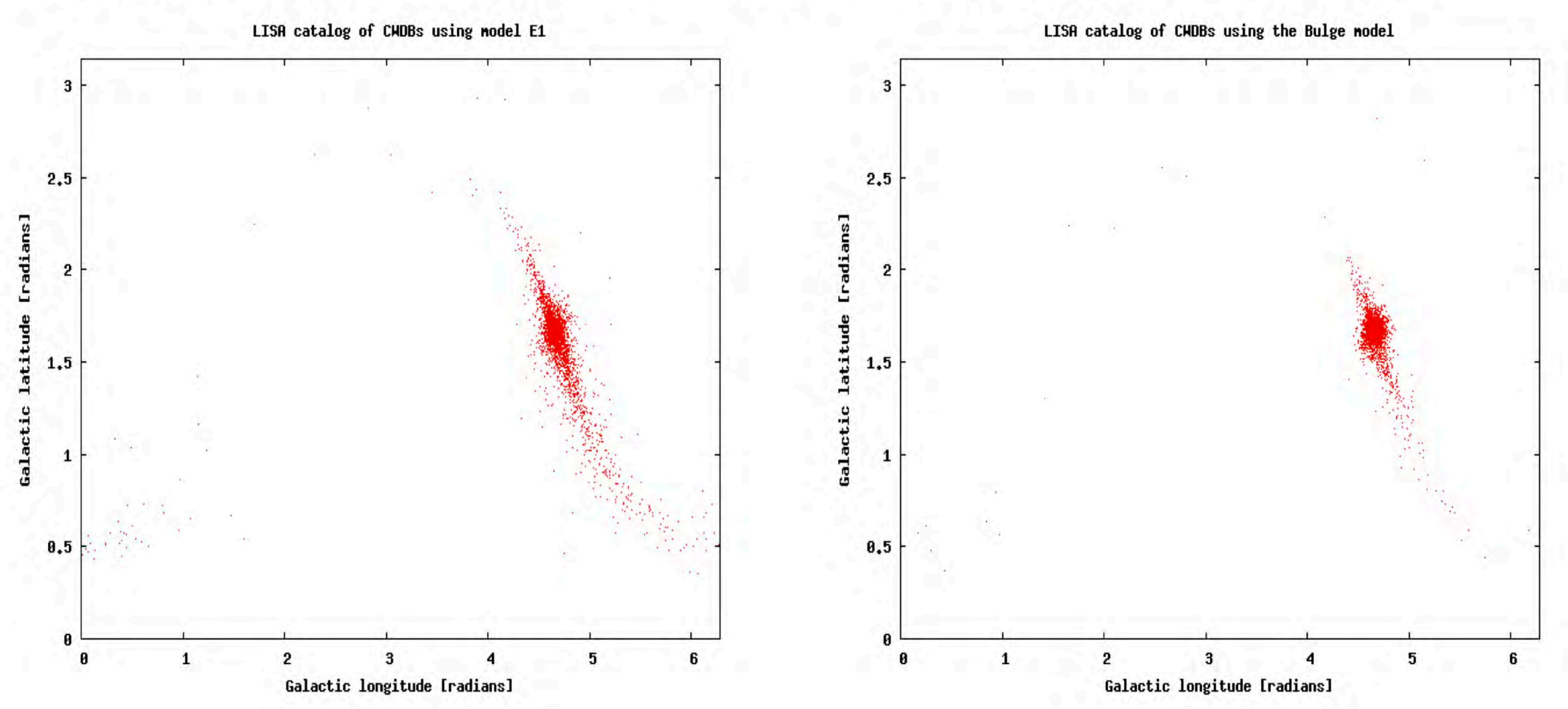

Figure 3: LISA detections from observing different Galaxy models, E1 (left) and bulge (right).

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